

PARATHYROID HORMONE RECEPTOR ACTIVATION AND HEMATOPOIETIC PROGENITOR CELL EXPANSION

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Field of the Invention

The invention includes methods for manipulating hematopoietic progenitor cells and related products. In particular the invention includes methods and products for enhancing the growth and maintenance of hematopoietic progenitor cells both *in vivo* and *in vitro*, for enhancing mobilization of hematopoietic progenitor cells, for improving the efficiency of targeting cells to the bone marrow, and/or for modulating hematopoietic progenitor cell function.

Background of the Invention

Circulating blood cells, such as erythrocytes, leukocytes, platelets and lymphocytes, arise from the terminal differentiation of precursor cells, in a process referred to as hematopoiesis. In fetal life, hematopoiesis occurs throughout the reticular endothelial system. In the normal adult, terminal differentiation of the precursor cells occurs exclusively in the marrow cavities of the axial skeleton, with some extension into the proximal femora and humeri. These precursor cells, in turn, derive from immature cells, called progenitors, stem cells or hematopoietic cells.

Hematopoietic progenitor cells have therapeutic potential as a result of their capacity to restore blood and immune cell function in transplant recipients as well as their potential ability to generate cells for other tissues such as brain, muscle and liver (Choi, 1998 *Biochem Cell Biol* 76, 947-56; Eglitis and Mezey, 1997 *Proc Natl Acad Sci U S A* 94, 4080-5; Gussoni et al., 1999 *Nature* 401, 390-4; Theise et al., 2000 *Hepatology* 32, 11-6). Human autologous and allogeneic bone marrow transplantation methods are currently used as therapies for diseases such as leukemia, lymphoma, and other life-threatening diseases. For these procedures a large amount of donor bone marrow must be isolated to ensure that there are

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enough cells for engraftment. Hematopoietic progenitor cell expansion for bone marrow transplantation is a potential method for generating human long-term bone marrow cultures for these therapeutic utilities. Several studies have reported the isolation and purification of hematopoietic progenitor cells (see, e.g., U.S. Patent No. 5,061,620), but none of these
5 methods have been overwhelmingly successful.

Determining the basis for progenitor cell localization is important to maximizing the therapeutic potential of those cells. During development, hematopoiesis translocates from the fetal liver to the bone marrow, which then remains the site of hematopoiesis throughout adulthood. Once hematopoiesis has been established in the bone marrow, the hematopoietic
10 progenitor cells are not distributed randomly throughout the bone cavity. Instead, the hematopoietic progenitor cells are found in close proximity to the endosteal surfaces (Lord et al., 1975, Blood, 46:65-72; Gong et al., 1978, Science, 199:1443-1445), an observation recently confirmed when injected purified hematopoietic progenitor cells were found to preferentially localize to the endosteal surfaces approximately 10 hours following injection
15 (Nilsson, et al., 2001, Blood, 97:2293-2299). The more mature progenitor cells (as measured by their CFU-C activity) increased in number as the distance from the bone surface increased. Finally, as the central longitudinal axis of the bone is approached, it has been shown that terminal differentiation of mature cells occurs (Lord et al., 1975, Blood, 46:65-72; Cui et al., 1996, Cell Prolif., 29:243-257; Lord et al., 1990, Int. J. Cell Clon., 8:317-331).

Given the relationship between the hematopoietic progenitor cells and the endosteal surfaces of the bone, one cell type that has been implicated in playing a role in hematopoiesis is the osteoblast (Taichman and Emerson, 1998, Stem Cells, 16:7-15). Osteoblastic cells are skeletal cells responsible for the production and mineralization of bone matrix, in response to local and hormonal stimuli (Ducy, et al., 2000, Science, 289:1501-1504). In addition, these
25 cells regulate bone remodeling by modulating the formation and activity of osteoclasts, bone-resorbing cells of hematopoietic origin, through the RANK/RANK-Ligand system (Teitelbaum et al., 2000, Science, 289:1504-1508). Studies have demonstrated that osteoblastic cells can support the growth of primitive hematopoietic cells, through the release of G-CSF and other growth factors (Taichman and Emerson, 1994, J. Exp. Med., 179:1677-
30 1682; Taichman et al., 1996, Blood, 87:518-524; Taichman et al., 2001, Br. J. Haematol., 112:438-448).

The ability to manipulate progenitor cells could improve the efficiency of engraftment of transplanted cells. Currently, transplantation techniques are extremely inefficient. In view of their enormous therapeutic potential relatively little is known about how hematopoietic progenitor cells are regulated, e.g., what factors cause cell localization, expansion, etc. Some studies have suggested that progenitor cell localization into the bone marrow space is chemokine dependent. For instance, the absence of either SDF-1 or its receptor, CXCR-4, was found to preclude localization of hematopoiesis in the bone marrow in developing mice (Nagasawa et al., 1996, *Nature*, 382:635-8; Su et al., 1999, *J Immunol.*, 162:7128-7132; Zou et al., 1998, *Nature*, 393:595-9). In addition, manipulation of CXCR-4 alters the homing and retention of progenitors in adult mice further supporting its critical role (Ma et al., 1999, *Immunity*, 10:463-71; Peled et al., 1999, *Science*, 283:845-8). Selectins and integrins are also believed to participate in this process and have been identified as mediators of retention or adhesion of primitive cells to bone marrow *in vivo* or *in vitro* (Greenberg et al., 2000, *Blood*, 95:478-86; Naiyer et al., 1999, *Blood*, 94:4011-9; Rood et al., 1999, *Exp. Hematol.*, 27:1306-14; van der Loo et al., 1998, *J. Clin. Invest.* 102:1051-61; Williams et al., 1991, *Nature*, 352:438-41; Zanjani et al., 1999, *Blood*, 94:2515-22). These studies, however, have not provided a complete understanding of progenitor cell localization.

Understanding exogenous signaling molecules which may contribute to the expansion of the progenitor cell population is important to defining therapeutic procedures.

Summary of the Invention

The invention relates in some aspects to methods for manipulating hematopoietic progenitor cells. Hematopoietic progenitor cells undergo a development stage-specific translocation during ontogeny and ultimately reside in the adult bone marrow. Maintenance of this highly regenerative cell pool through adult life is dependent upon the bone marrow microenvironment. It has been discovered, surprisingly, that activation of the Parathyroid Hormone/Parathyroid Hormone-related Protein (PTH/PTHrP) receptor in cells forming this microenvironment according to the invention leads to an enhancement in the growth (including increase in self-renewal/number increase) and/or maintenance of hematopoietic progenitor cells.

Thus, in one aspect the invention relates to a method for enhancing the growth or maintenance of hematopoietic progenitor cells. The method involves, contacting a cell

expressing a PTH/PTHrP receptor with an agent that activates the PTH/PTHrP receptor in an amount effective to support the growth or maintenance of hematopoietic progenitor cells. In important embodiments, the cell expressing a PTH/PTHrP receptor is present in the immediate vicinity of a hematopoietic progenitor cell. In one embodiment, the cell
5 expressing a PTH/PTHrP receptor is a lymphoreticular stromal cell. In a further embodiment, the cell expressing a PTH/PTHrP receptor is a hematopoietic progenitor cell. Contacting of the cell expressing a PTH/PTHrP receptor with an agent that activates the PTH/PTHrP receptor may occur *in vitro* or *in vivo*. In important embodiments, the agent that activates the PTH/PTHrP receptor is PTH (including recombinant synthetic human PTH (1-
10 34) and active PTH fragments), a PTH analogue, or a PTH/PTHrP receptor agonist. The growth or maintenance of hematopoietic progenitor cells may occur *in vitro* or *in vivo*.

In another aspect of the invention a method for inducing hematopoietic progenitor cell self-renewal, is provided. The method involves co-culturing a hematopoietic progenitor cell with a cell expressing a PTH/PTHrP receptor, and contacting the cell expressing a
15 PTH/PTHrP receptor with an agent that activates the PTH/PTHrP receptor to induce self-renewal of the hematopoietic progenitor cell. The co-culturing may occur *in vitro* or *ex vivo*.

In a further aspect of the invention a method for enhancing the growth or maintenance of hematopoietic progenitor cells in a subject, is provided. The method involves administering to a subject in need of such treatment an agent that activates the PTH/PTHrP
20 receptor in cells of the subject expressing the PTH/PTHrP receptor, in an amount effective to support the growth or maintenance of hematopoietic progenitor cells. In some embodiments, the cell expressing a PTH/PTHrP receptor is a lymphoreticular stromal cell. In certain embodiments, the cell expressing a PTH/PTHrP receptor is a hematopoietic progenitor cell. In important embodiments, the agent that activates the PTH/PTHrP receptor is PTH, a PTH
25 analogue, or a PTH/PTHrP receptor agonist. In further important embodiments, the subject in need of such treatment is a bone marrow donor. The bone marrow donor may have donated bone marrow, or has yet to donate bone marrow. In certain embodiments, the subject in need of such treatment is a bone marrow transplant recipient. In one embodiment, the subject in need of such treatment is a subject having hematopoietic progenitor cells under
30 environmental stress. Environmental stresses include increased temperatures (e.g., fever), physical trauma, oxidative, osmotic and chemical stress (e.g. a chemotherapeutic agent), and/or irradiation (e.g. ultra-violet (UV), X-ray, gamma, alpha, or beta irradiation).

In further embodiments the subject in need of such treatment is a subject having immune system deficiencies. Immune system deficiencies include subjects with chronic infections, subjects treated with radiation or chemotherapy, subjects with abnormally low CD4 cell counts, subjects with genetic immune deficiencies. The subject can also be a
5 subject with any one or more categories of hematopoietic cell deficiency such as abnormally low monocytes, macrophages, neutrophils, T-cells, B-cells, erythrocytes, platelets, basophils.

According to another aspect of the invention a method for enhancing mobilization of hematopoietic progenitor cells, is provided. The method involves administering to a subject in need of such treatment an agent that activates a PTH/PTHrP receptor in an amount
10 sufficient to enhance mobilization of hematopoietic progenitor cells in the subject. In important embodiments, the subject is a bone marrow donor.

According to a further aspect, the invention provides an isolated population of cells treated with PTH. The population of cells is preferably a stromal cell population. The cells can be *ex vivo* cells isolated from a subject. Alternatively, the cells can be *in vitro* cultured
15 cells. In one embodiment, the isolated cells are homogeneous. In an alternative embodiment, the isolated cells are heterogeneous and include two or more cell types. One of the cell types is preferably a stromal cell.

Each of the limitations of the invention can encompass various embodiments of the invention. It is, therefore, anticipated that each of the limitations of the invention involving
20 any one element or combinations of elements can be included in each aspect of the invention.

Brief Description of the Drawings

Figure 1. Figure showing hPTH/PTHrP receptor construct.

Figure 2. a) Graph showing the frequency of Sca-1⁺lin⁻ subpopulation cells from
25 total bone marrow mononuclear cells. b) Graph showing hematopoietic stem cell frequency of lin⁻ fraction of bone marrow mononuclear cells. c) Plot showing proportion of Sca-1⁺lin⁻ cells in G₀ vs G₁ phase. d) Graph showing frequency of hematopoietic stem cells using the CFU-C assay.

Figure 3. a) Graph showing support of stromal cells from transgenic mice. b) Plot
30 showing the level of NICD in lin⁻Sca-1⁺c-Kit⁺ hematopoietic stem cells.

Figure 4. Graph showing LTC-IC assay under non-contact culture conditions.

Figure 5. a) Graph showing LTC-IC assay of C57B1/6 stroma expansion in the absence or presence of PTH. b) Photo showing alkaline phosphatase positive cells. c) Graph showing inhibition of LTC-IC in the presence or absence of PTH. d) Graph showing percentage of $\text{lin}^{-}\text{Sca-1}^{+}\text{c-Kit}^{+}$ cells in bone marrow in mock injected and PTH injected mice. e) Graph showing increase of LTC-ICs in bone marrow mononuclear cells in mock injected and PTH injected mice. f) Graph showing percentage of CD45.2^{+} cells in bone marrow in mock injected and PTH injected mice. g) Graph showing CFU-Cs in bone marrow mononuclear cells in mock injected and PTH injected mice.

Figure 6. Plot showing percent survival of mock injected and PTH injected mice.

Detailed Description of the Invention

New methods for manipulating hematopoietic progenitor cells have been identified according to the invention. These methods and related products have great therapeutic and research value. For instance, hematopoietic progenitor cells are used for transplantation to supplement the immune system of immune deficient patients. These cells have many additional therapeutic uses. Prior to the invention, however, the ability to isolate and purify hematopoietic progenitor cells has been limited. These cells reside in the bone marrow, making their isolation a technically complex procedure. Additionally, there are not many commercially viable methods for identifying these cells in a sample. The invention has solved many of these problems.

It has been discovered according to some aspects of the invention that activation of the parathyroid hormone/parathyroid hormone-related protein receptor (PTH/PTHrP) results in enhancing the growth (including increase in self-renewal/number increase) or maintenance of hematopoietic progenitor cells. This effect is believed to be mediated by cells expressing the receptor that are present in the bone marrow microenvironment. An agent that activates the receptor (such as parathyroid hormone- PTH), may therefore serve as a stimulant to enhance progenitor cell production *in vivo* and *in vitro*. This represents an unexpected discovery with important clinical implications for the field of progenitor cell transplantation.

Expanding the number of bone marrow derived progenitor cells is a long-sought solution to the inadequate number of progenitor cells available for transplantation in hematologic and oncologic disease. A beneficial effect could be envisioned in at least the following settings: (i) the enhancement of progenitor cell numbers *in vivo*; this could be

either prior to harvest to facilitate obtaining progenitor cells, or to accelerate progenitor cell recovery following bone marrow transplantation, and/or (ii) *ex vivo* expansion of harvested stem cells. A method to increase progenitor cell numbers *in vivo* would potentially reduce the time and discomfort associated with bone marrow/peripheral progenitor cell harvesting and increase the pool of progenitor cell donors. Currently approximately 25% of autologous donor transplants are prohibited for lack of sufficient progenitor cells. In addition, less than 25% of patients in need of allogeneic transplant can find a histocompatible donor. Umbilical cord blood banks currently exist and cover the broad racial make-up of the general population, but are currently restricted in use to children due to inadequate progenitor cell numbers in the specimens. A method to increase progenitor cell numbers would permit cord blood to be useful for adult patients, thereby expanding the use of allogeneic transplantation.

According to the invention, a method for enhancing the growth or maintenance of hematopoietic progenitor cells is provided. The method involves, contacting a cell expressing a PTH/PTHrP receptor with an agent that activates the PTH/PTHrP receptor in an amount effective to support the growth or maintenance of hematopoietic progenitor cells.

"Hematopoietic progenitor cells" (or Hematopoietic stem cells) as used herein refer to immature blood cells having the capacity to self-renew and to differentiate into the more mature blood cells (also described herein as "progeny") comprising granulocytes (e.g., promyelocytes, neutrophils, eosinophils, basophils), erythrocytes (e.g., reticulocytes, erythrocytes), thrombocytes (e.g., megakaryoblasts, platelet producing megakaryocytes, platelets), and monocytes (e.g., monocytes, macrophages). Hematopoietic progenitor cells are interchangeably described as "stem cells" throughout the specification. It is known in the art that such cells may or may not include CD34⁺ cells. CD34⁺ cells are immature cells present in the "blood products" described below, express the CD34 cell surface marker, and are believed to include a subpopulation of cells with the "progenitor cell" properties defined above. It is well known in the art that hematopoietic progenitor cells include pluripotent stem cells, multipotent progenitor cells (e.g., a lymphoid stem cell), and/or progenitor cells committed to specific hematopoietic lineages. The progenitor cells committed to specific hematopoietic lineages may be of T cell lineage, B cell lineage, dendritic cell lineage, Langerhans cell lineage and/or lymphoid tissue-specific macrophage cell lineage.

The hematopoietic progenitor cells can be obtained from blood products. A "blood product" as used in the present invention defines a product obtained from the body or an organ of the body containing cells of hematopoietic origin. Such sources include unfractionated bone marrow, umbilical cord, peripheral blood, liver, thymus, lymph and spleen. It will be apparent to those of ordinary skill in the art that all of the aforementioned crude or unfractionated blood products can be enriched for cells having "hematopoietic progenitor cell" characteristics in a number of ways. For example, the blood product can be depleted from the more differentiated progeny. The more mature, differentiated cells can be selected against, via cell surface molecules they express. Additionally, the blood product can be fractionated selecting for CD34⁺ cells. As mentioned earlier, CD34⁺ cells are thought in the art to include a subpopulation of cells capable of self-renewal and pluripotentiality. Such selection can be accomplished using, for example, commercially available magnetic anti-CD34 beads (Dynal, Lake Success, NY). Unfractionated blood products can be obtained directly from a donor or retrieved from cryopreservative storage.

In important embodiments, the cell expressing a PTH/PTHrP receptor is present in the immediate vicinity of a hematopoietic progenitor cell. In certain embodiments, the cell expressing a PTH/PTHrP receptor is a lymphoreticular stromal cell. "Lymphoreticular stromal cells" as used herein may include, but are not limited to, all cell types present in a lymphoid tissue which are not lymphocytes or lymphocyte precursors or progenitors, e.g., osteoblasts, epithelial cells, endothelial cells, mesothelial cells, dendritic cells, splenocytes and macrophages. Lymphoreticular stromal cells also include cells that would not ordinarily function as lymphoreticular stromal cells, such as fibroblasts, which have been genetically altered to secrete or express on their cell surface the factors necessary for the maintenance, growth and/or differentiation of hematopoietic progenitor cells, including their progeny. Lymphoreticular stromal cells are derived from the disaggregation of a piece of lymphoid tissue (see discussion below). Such cells according to the invention are capable of supporting *in vitro* the maintenance, growth and/or differentiation of hematopoietic progenitor cells, including their progeny. By "lymphoid tissue" it is meant to include bone marrow, peripheral blood (including mobilized peripheral blood), umbilical cord blood, placental blood, fetal liver, embryonic cells (including embryonic stem cells), aortal-gonadal-mesonephros derived cells, and lymphoid soft tissue. "Lymphoid soft tissue" as used herein includes, but is not

limited to, tissues such as thymus, spleen, liver, lymph node, skin, tonsil, adenoids and Peyer's patch, and combinations thereof.

Lymphoreticular stromal cells provide the supporting microenvironment in the intact lymphoid tissue for the maintenance, growth and/or differentiation of hematopoietic progenitor cells, including their progeny. The microenvironment includes soluble and cell surface factors expressed by the various cell types which comprise the lymphoreticular stroma. Generally, the support which the lymphoreticular stromal cells provide may be characterized as both contact-dependent and non-contact-dependent.

Lymphoreticular stromal cells may be autologous ("self") or non-autologous ("non-self," e.g., allogeneic, syngeneic or xenogeneic) with respect to hematopoietic progenitor cells or antigen presenting cells. "Autologous," as used herein, refers to cells from the same subject. "Allogeneic," as used herein, refers to cells of the same species that differ genetically to the cell in comparison. "Syngeneic," as used herein, refers to cells of a different subject that are genetically identical to the cell in comparison. "Xenogeneic," as used herein, refers to cells of a different species to the cell in comparison. Lymphoreticular stroma cells may be obtained from the lymphoid tissue of a human or a non-human subject at any time after the organ/tissue has developed to a stage (i.e., the maturation stage) at which it can support the maintenance growth and/or differentiation of hematopoietic progenitor cells. The stage will vary between organs/tissues and between subjects. In primates, for example, the maturation stage of thymic development is achieved during the second trimester. At this stage of development the thymus can produce peptide hormones such as thymulin, α_1 and β_4 -thymosin, and thymopoietin, as well as other factors required to provide the proper microenvironment for T cell differentiation. The different maturation stages for the different organs/tissues and between different subjects are well known in the art.

Lymphoreticular stromal cells, preferably express the PTH/PTHrP receptor. The lymphoid tissue from which lymphoreticular stromal cells are derived usually determines the lineage-commitment hematopoietic progenitor cells undertake, resulting in the lineage-specificity of the differentiated progeny. In certain embodiments, the lymphoreticular stromal cells are thymic stromal cells and the multipotent progenitor cells and/or committed progenitor cells are committed to a T cell lineage. In other embodiments, the lymphoreticular stromal cells may be splenic stromal cells and the multipotent progenitor cells and/or committed progenitor cells are committed to a B cell lineage. Also surprising, according to the invention, has been

the discovery that the highest yield of differentiated progeny occurs when human hematopoietic progenitor cells are cultured in the presence of xenogeneic (non-human) lymphoreticular stromal cells. Preferably the xenogeneic lymphoreticular stromal cells are of murine origin.

5 Various other embodiments are provided, wherein the lymphoreticular stromal cells may be genetically altered. In certain embodiments, lymphoreticular stromal cells, preferably express the PTH/PTHrP receptor (endogenously or via genetic alteration). The lymphoreticular stromal cells may be transfected with exogenous DNA that encodes, for example, one of the hematopoietic growth factors described elsewhere herein.

10 As mentioned earlier, lymphoreticular stromal cells are derived from the disaggregation of a piece of lymphoid tissue, forming cell suspensions. Preferably, single cell suspensions are generated. These lymphoreticular stromal cell suspensions may be used directly, or made non-mitotic by procedures standard in the tissue culture art. Examples of such methods are irradiation of lymphoreticular stromal cells with a gamma-ray source or
15 incubation of the cells with mitomycin C for a sufficient amount of time to render the cells mitotically inactive. Mitotic inactivation is preferred when the lymphoreticular stromal cells are of human origin (to eliminate progenitor cells that may be present in the suspension). The lymphoreticular stromal cells may then be seeded into a three-dimensional matrix of the invention and permitted to attach to a surface of the porous, solid matrix. It should be noted
20 that the lymphoreticular stromal cells may alternatively be cryopreserved for later use or for storage and shipment to remote locations, such as for use in connection with the sale of kits. Cryopreservation of cells cultured *in vitro* is well established in the art. Subsequent to isolation (and/or mitotic inactivation) of a cell sample, cells may be cryopreserved by first suspending the cells in a cryopreservation medium and then gradually freezing the cell
25 suspension. Frozen cells are typically stored in liquid nitrogen or at an equivalent temperature in a medium containing serum and a cryopreservative such as dimethyl sulfoxide.

 The co-culture of hematopoietic progenitor cells (and progeny thereof) with lymphoreticular stromal cells, according to certain aspects of the invention preferably occurs
30 under conditions sufficient to produce a percent increase in the number of lymphoid tissue origin cells deriving from the hematopoietic progenitor cells. The conditions used refer to a combination of conditions known in the art (e.g., temperature, CO₂ and O₂ content, nutritive

media, time-length, etc.). The time sufficient to increase the number of cells is a time that can be easily determined by a person skilled in the art, and can vary depending upon the original number of cells seeded. The amounts of hematopoietic progenitor cells and lymphoreticular stromal cells initially introduced (and subsequently seeded) into the porous solid matrix may vary according to the needs of the experiment. The ideal amounts can be easily determined by a person skilled in the art in accordance with needs. Hematopoietic progenitor cells may be added at different numbers. As an example, discoloration of the media over a certain period of time can be used as an indicator of confluency. Additionally, and more precisely, different numbers of hematopoietic progenitor cells or volumes of the blood product can be cultured under identical conditions, and cells can be harvested and counted over regular time intervals, thus generating the "control curves". These "control curves" can be used to estimate cell numbers in subsequent assays.

The conditions for determining colony forming potential are similarly determined. Colony forming potential is the ability of a cell to form progeny. Assays for this are well known to those of ordinary skill in the art and include seeding cells into a semi-solid matrix, treating them with growth factors, and counting the number of colonies.

In preferred embodiments of the invention, the hematopoietic progenitor cells may be harvested. "Harvesting" hematopoietic progenitor cells is defined as the dislodging or separation of cells from the matrix. This can be accomplished using a number of methods, such as enzymatic, non-enzymatic, centrifugal, electrical, or size-based methods, or preferably, by flushing the cells using media (e.g. media in which the cells are incubated). The cells can be further collected, separated, and further expanded generating even larger populations of differentiated progeny.

As mentioned above, the hematopoietic progenitor cells, and progeny thereof, can be genetically altered. Genetic alteration of a hematopoietic progenitor cell includes all transient and stable changes of the cellular genetic material which are created by the addition of exogenous genetic material. Examples of genetic alterations include any gene therapy procedure, such as introduction of a functional gene to replace a mutated or nonexpressed gene, introduction of a vector that encodes a dominant negative gene product, introduction of a vector engineered to express a ribozyme and introduction of a gene that encodes a therapeutic gene product. Natural genetic changes such as the spontaneous rearrangement of a T cell receptor gene without the introduction of any agents are not included in this

embodiment. Exogenous genetic material includes nucleic acids or oligonucleotides, either natural or synthetic, that are introduced into the hematopoietic progenitor cells. The exogenous genetic material may be a copy of that which is naturally present in the cells, or it may not be naturally found in the cells. It typically is at least a portion of a naturally occurring gene which has been placed under operable control of a promoter in a vector construct.

Various techniques may be employed for introducing nucleic acids into cells. Such techniques include transfection of nucleic acid-CaPO₄ precipitates, transfection of nucleic acids associated with DEAE, transfection with a retrovirus including the nucleic acid of interest, liposome mediated transfection, and the like. For certain uses, it is preferred to target the nucleic acid to particular cells. In such instances, a vehicle used for delivering a nucleic acid according to the invention into a cell (e.g., a retrovirus, or other virus; a liposome) can have a targeting molecule attached thereto. For example, a molecule such as an antibody specific for a surface membrane protein on the target cell or a ligand for a receptor on the target cell can be bound to or incorporated within the nucleic acid delivery vehicle. For example, where liposomes are employed to deliver the nucleic acids of the invention, proteins which bind to a surface membrane protein associated with endocytosis may be incorporated into the liposome formulation for targeting and/or to facilitate uptake. Such proteins include proteins or fragments thereof tropic for a particular cell type, antibodies for proteins which undergo internalization in cycling, proteins that target intracellular localization and enhance intracellular half life, and the like. Polymeric delivery systems also have been used successfully to deliver nucleic acids into cells, as is known by those skilled in the art. Such systems even permit oral delivery of nucleic acids.

In the present invention, the preferred method of introducing exogenous genetic material into hematopoietic cells is by transducing the cells *in situ* on the matrix using replication-deficient retroviruses. Replication-deficient retroviruses are capable of directing synthesis of all virion proteins, but are incapable of making infectious particles. Accordingly, these genetically altered retroviral vectors have general utility for high-efficiency transduction of genes in cultured cells, and specific utility for use in the method of the present invention. Retroviruses have been used extensively for transferring genetic material into cells. Standard protocols for producing replication-deficient retroviruses (including the steps of incorporation of exogenous genetic material into a plasmid, transfection of a packaging

cell line with plasmid, production of recombinant retroviruses by the packaging cell line, collection of viral particles from tissue culture media, and infection of the target cells with the viral particles) are provided in the art.

5 The major advantage of using retroviruses is that the viruses insert efficiently a single copy of the gene encoding the therapeutic agent into the host cell genome, thereby permitting the exogenous genetic material to be passed on to the progeny of the cell when it divides. In addition, gene promoter sequences in the LTR region have been reported to enhance expression of an inserted coding sequence in a variety of cell types. The major disadvantages of using a retrovirus expression vector are (1) insertional mutagenesis, i.e., the insertion of
10 the therapeutic gene into an undesirable position in the target cell genome which, for example, leads to unregulated cell growth and (2) the need for target cell proliferation in order for the therapeutic gene carried by the vector to be integrated into the target genome. Despite these apparent limitations, delivery of a therapeutically effective amount of a therapeutic agent via a retrovirus can be efficacious if the efficiency of transduction is high
15 and/or the number of target cells available for transduction is high.

Yet another viral candidate useful as an expression vector for transformation of hematopoietic cells is the adenovirus, a double-stranded DNA virus. Like the retrovirus, the adenovirus genome is adaptable for use as an expression vector for gene transduction, i.e., by removing the genetic information that controls production of the virus itself. Because the
20 adenovirus functions usually in an extrachromosomal fashion, the recombinant adenovirus does not have the theoretical problem of insertional mutagenesis. On the other hand, adenoviral transformation of a target hematopoietic cell may not result in stable transduction. However, more recently it has been reported that certain adenoviral sequences confer intrachromosomal integration specificity to carrier sequences, and thus result in a stable
25 transduction of the exogenous genetic material.

Thus, as will be apparent to one of ordinary skill in the art, a variety of suitable vectors are available for transferring exogenous genetic material into hematopoietic cells. The selection of an appropriate vector to deliver a therapeutic agent for a particular condition amenable to gene replacement therapy and the optimization of the conditions for insertion of
30 the selected expression vector into the cell, are within the scope of one of ordinary skill in the art without the need for undue experimentation. The promoter characteristically has a specific nucleotide sequence necessary to initiate transcription. Optionally, the exogenous

genetic material further includes additional sequences (i.e., enhancers) required to obtain the desired gene transcription activity. For the purpose of this discussion an "enhancer" is simply any nontranslated DNA sequence which works contiguous with the coding sequence (in cis) to change the basal transcription level dictated by the promoter.

- 5 Preferably, the exogenous genetic material is introduced into the hematopoietic cell genome immediately downstream from the promoter so that the promoter and coding sequence are operatively linked so as to permit transcription of the coding sequence. A preferred retroviral expression vector includes an exogenous promoter element to control transcription of the inserted exogenous gene. Such exogenous promoters include both constitutive and inducible
10 promoters.

Naturally-occurring constitutive promoters control the expression of essential cell functions. As a result, a gene under the control of a constitutive promoter is expressed under all conditions of cell growth. Exemplary constitutive promoters include the promoters for the following genes which encode certain constitutive or "housekeeping" functions:

- 15 hypoxanthine phosphoribosyl transferase (HPRT), dihydrofolate reductase (DHFR) (Scharfmann et al., 1991, Proc. Natl. Acad. Sci. USA, 88:4626-4630), adenosine deaminase, phosphoglycerol kinase (PGK), pyruvate kinase, phosphoglycerol mutase, the actin promoter (Lai et al., 1989, Proc. Natl. Acad. Sci. USA, 86:10006-10010), and other constitutive promoters known to those of skill in the art. In addition, many viral promoters function
20 constitutively in eukaryotic cells. These include: the early and late promoters of SV40; the long terminal repeats (LTRS) of Moloney Leukemia Virus and other retroviruses; and the thymidine kinase promoter of Herpes Simplex Virus, among many others. Accordingly, any of the above-referenced constitutive promoters can be used to control transcription of a heterologous gene insert.

- 25 Genes that are under the control of inducible promoters are expressed only or to a greater degree, in the presence of an inducing agent, (e.g., transcription under control of the metallothionein promoter is greatly increased in presence of certain metal ions). Inducible promoters include responsive elements (REs) which stimulate transcription when their inducing factors are bound. For example, there are REs for serum factors, steroid hormones,
30 retinoic acid and cyclic AMP. Promoters containing a particular RE can be chosen in order to obtain an inducible response and in some cases, the RE itself may be attached to a different promoter, thereby conferring inducibility to the recombinant gene. Thus, by selecting the

appropriate promoter (constitutive versus inducible; strong versus weak), it is possible to control both the existence and level of expression of a therapeutic agent in the genetically modified hematopoietic cell. Selection and optimization of these factors for delivery of a therapeutically effective dose of a particular therapeutic agent is deemed to be within the scope of one of ordinary skill in the art without undue experimentation, taking into account the above-disclosed factors and the clinical profile of the patient.

In addition to at least one promoter and at least one heterologous nucleic acid encoding the therapeutic agent, the expression vector preferably includes a selection gene, for example, a neomycin resistance gene, for facilitating selection of hematopoietic cells that have been transfected or transduced with the expression vector. Alternatively, the hematopoietic cells are transfected with two or more expression vectors, at least one vector containing the gene(s) encoding the therapeutic agent(s), the other vector containing a selection gene. The selection of a suitable promoter, enhancer, selection gene and/or signal sequence (described below) is deemed to be within the scope of one of ordinary skill in the art without undue experimentation.

The selection and optimization of a particular expression vector for expressing a specific gene product in an isolated hematopoietic cell is accomplished by obtaining the gene, preferably with one or more appropriate control regions (e.g., promoter, insertion sequence); preparing a vector construct comprising the vector into which is inserted the gene; transfecting or transducing cultured hematopoietic cells *in vitro* with the vector construct; and determining whether the gene product is present in the cultured cells.

Table 1. Human Gene Therapy Protocols Approved by RAC: 1990-1994

Severe combined immune deficiency (SCID) due to ADA deficiency	Autologous lymphocytes transduced with human ADA gene	7/31/90
Advanced cancer	Tumor-infiltrating lymphocytes transduced with tumor necrosis factor gene	7/31/90
Advanced cancer	Immunization with autologous cancer cells transduced with tumor necrosis factor gene	10/07/91
Advanced cancer	Immunization with autologous cancer cells transduced with interleukin-2 gene	10/07/91
Asymptomatic patients infected with HIV-1	Murine Retro viral vector encoding HIV-1 genes [HIV-IT(V)]	6/07/93

AIDS	Effects of a transdominant form of <i>rev</i> gene on AIDS intervention	6/07/93
Advanced cancer	Human multiple-drug resistance (MDR) gene transfer	6/08/93
HIV infection	Autologous lymphocytes transduced with catalytic ribozyme that cleaves HIV-1 RNA (Phase I study)	9/10/93
Metastatic melanoma	Genetically engineered autologous tumor vaccines producing interleukin-2	9/10/93
HIV infection	Murine Retro viral vector encoding HIV-IT(V) genes (open label Phase I/II trial)	12/03/93
HIV infection (identical twins)	Adoptive transfer of syngeneic cytotoxic T lymphocytes (Phase I/II pilot study)	3/03/94
Breast cancer (chemo-protection during therapy)	Use of modified Retro virus to introduce chemotherapy resistance sequences into normal hematopoietic cells (pilot study)	6/09/94
Fanconi's anemia	Retro viral mediated gene transfer of the Fanconi anemia complementation group C gene to hematopoietic progenitors	6/09/94
Metastatic prostate carcinoma	Autologous human granulocyte macrophage-colony stimulating factor gene transduced prostate cancer vaccine *(first protocol to be approved under the accelerated review process; ORDA=Office of Recombinant DNA Activities)	ORDA/NIH 8/03/94*
Metastatic breast cancer	<i>In vivo</i> infection with breast-targeted Retro viral vector expressing antisense <i>c-fos</i> or antisense <i>c-myc</i> RNA	9/12/94
Metastatic breast cancer (refractory or recurrent)	Non-viral system (liposome-based) for delivering human interleukin-2 gene into autologous tumor cells (pilot study)	9/12/94
Mild Hunter syndrome	Retro viral-mediated transfer of the iduronate-2-sulfatase gene into lymphocytes	9/13/94
Advanced mesothelioma	Use of recombinant adenovirus (Phase I study)	9/13/94

The foregoing (Table 1), represent only examples of genes that can be delivered according to the methods of the invention. Suitable promoters, enhancers, vectors, etc., for such genes are published in the literature associated with the foregoing trials. In general,

5 useful genes replace or supplement function, including genes encoding missing enzymes such as adenosine deaminase (ADA) which has been used in clinical trials to treat ADA deficiency and cofactors such as insulin and coagulation factor VIII. Genes which affect regulation can also be administered, alone or in combination with a gene supplementing or replacing a specific function. For example, a gene encoding a protein which suppresses expression of a
10 particular protein-encoding gene can be administered. The invention is particularly useful in delivering genes which stimulate the immune response, including genes encoding viral antigens, tumor antigens, cytokines (e.g. tumor necrosis factor) and inducers of cytokines (e.g. endotoxin).

Employing the culture conditions described in greater detail below, it is possible
15 according to the invention to preserve hematopoietic progenitor cells and to stimulate the

expansion of hematopoietic progenitor cell number and/or colony forming unit potential. Once expanded, the cells, for example, can be returned to the body to supplement, replenish, etc. a patient's hematopoietic progenitor cell population. This might be appropriate, for example, after an individual has undergone chemotherapy. There are certain genetic conditions wherein hematopoietic progenitor cell numbers are decreased, and the methods of the invention may be used in these situations as well.

It also is possible to take the increased numbers of hematopoietic progenitor cells produced according to the invention and stimulate them with hematopoietic growth agents that promote hematopoietic cell maintenance, expansion and/or differentiation, and also influence cell localization, to yield the more mature blood cells, *in vitro*. Such expanded populations of blood cells may be applied *in vivo* as described above, or may be used experimentally as will be recognized by those of ordinary skill in the art. Such differentiated cells include those described above, as well as T cells, plasma cells, erythrocytes, megakaryocytes, basophils, polymorphonuclear leukocytes, monocytes, macrophages, eosinophils and platelets.

In all of the *in vitro* and *ex vivo* culturing methods according to the invention, except as otherwise provided, the media used is that which is conventional for culturing cells. Examples include RPMI, DMEM, Iscove's, etc. Typically these media are supplemented with human or animal plasma or serum. Such plasma or serum can contain small amounts of hematopoietic growth factors. The media used according to the present invention, however, can depart from that used conventionally in the prior art.

The growth agents of particular interest in connection with the present invention are hematopoietic growth factors. By hematopoietic growth factors, it is meant factors that influence the survival, proliferation or differentiation of hematopoietic progenitor cells.

Growth agents that affect only survival and proliferation, but are not believed to promote differentiation, include the interleukins 3, 6 and 11, stem cell factor and FLT-3 ligand. Hematopoietic growth factors that promote differentiation include the colony stimulating factors such as GMCSF, GCSF, MCSF, Tpo, Epo, Oncostatin M, and interleukins other than IL-3, 6 and 11. The foregoing factors are well known to those of ordinary skill in the art. Most are commercially available. They can be obtained by purification, by recombinant methodologies or can be derived or synthesized synthetically.

"Stromal cell conditioned medium" refers to medium in which the
aforementioned lymphoreticular stromal cells have been incubated. The incubation is
performed for a period sufficient to allow the stromal cells to secrete factors into the medium.
Such "stromal cell conditioned medium" can then be used to supplement the culture of
5 hematopoietic progenitor cells promoting their proliferation and/or differentiation.

Thus, when cells are cultured without any of the foregoing agents, it is meant herein
that the cells are cultured without the addition of such agent except as may be present in
serum, ordinary nutritive media or within the blood product isolate, unfractionated or
fractionated, which contains the hematopoietic progenitor cells.

10 One method for modulating hematopoietic cell function according to the invention is
a method for enhancing mobilization of hematopoietic progenitor cells by using agents that
activate the PTH/PTHrP receptor. Current practice during bone marrow transplantation
involves the isolation of bone marrow cells from the bone marrow and/or peripheral blood of
donor subjects. About one third of these subjects do not "yield" enough hematopoietic
15 progenitor cells from their bone marrow and/or peripheral blood so that their marrow can be
considered suitable for transplantation. Using the methods of the invention, the "yield" may
be enhanced. For example, agents that activate the PTH/PTHrP receptor could result in
"mobilization" of hematopoietic progenitor cells and the efficiency of hematopoietic
progenitor cell isolation from subjects treated with such agents may be improved (especially
20 from the subject's peripheral blood). This then results in an increase in the number of donor
samples that may be used in transplantation.

Thus, in some aspects a method for enhancing mobilization of hematopoietic cells in a
subject is provided. The method involves administering to a subject an agent that activates
the PTH/PTHrP receptor to enhance mobilization of hematopoietic progenitor cells in the
25 subject.

As used herein, a subject is a human, non-human primate, cow, horse, pig, sheep,
goat, dog, cat or rodent. Human hematopoietic progenitor cells and human subjects are
particularly important embodiments.

As used herein a "an agent that activates the PTH/PTHrP receptor" is a compound
30 that includes Parathyroid hormone (PTH), parathyroid related-protein (PTHrP), and
analogues thereof.

The normal function of PTH is to maintain extracellular fluid calcium concentration. PTH acts directly on bone and kidney and indirectly on the intestines. PTH production in healthy individuals is closely regulated by the concentration of serum ionized calcium. Tendencies towards hypocalcemia, for example, induced by a calcium-deficient diet, are balanced by an increased PTH secretion. The increase in PTH levels increases the rate of bone resorption, thereby increasing the calcium flow from bone into blood, reduces the renal clearance of calcium, and increases the efficiency of calcium absorption in the intestines.

The physiological role of the parathyroid hormone-related protein (PTHrP) is not fully understood, but is thought to be acting principally as a paracrine or autocrine factor. PTHrP plays a role in fetal development as well as in adult physiology. PTHrP is produced by many cell types, including brain, pancreas, heart, lung, memory tissue, placenta, endothelial, and smooth muscle cells. In adults, PTHrP is thought to have little to do with calcium homeostasis, except in disease states.

PTH and PTHrP are distinct proteins and products of different genes. However, they share a similar bioactivity profile and a very limited sequence homology, indicating that they may have evolved from a common ancestral gene. Eight out of the 13 first amino acid residues at the N-terminus are identical. Both PTH, an 84 amino acid residues peptide, and PTHrP, a 139 to 173 amino acid residues peptide, bind to the PTH receptor (often referred to as the PTH/PTHrP receptor) and stimulate the same intracellular signaling pathways.

Parathyroid hormone (PTH) is an 84 amino acid polypeptide which is normally secreted from the parathyroid glands. PTH has an important physiological role to maintain serum calcium within a narrow range. Furthermore, it has anabolic properties when given intermittently. This has been well documented in a number of animal and open clinical studies, recently reviewed by Dempster, D. W. et al. (Endocrine Reviews 1993, vol. 14, 690-709). PTH has a multitude of effects on bone. Part of it is through the remodeling cycle. PTH causes both increased activation frequency and a positive balance per cycle. Human PTH may be obtained through peptide synthesis or from genetically engineered yeast, bacterial or mammalian cell hosts. Synthetic human PTH is commercially available from Bachem Inc., Bubendorf, Switzerland. Production of recombinant human parathyroid hormone is disclosed in e.g. EP-B-0383751.

The mature circulating form of parathyroid hormone is comprised of 84 amino acid residues. For most bone-related activities the truncated form of PTH, PTH(1-34), is a full agonist like the native 84 amino-acid hormone. Amino-terminal truncation results in polypeptides that are competitive antagonists of PTH-stimulated adenylate cyclase. For example, [Tyr³⁴]bPTH(7-34)NH₂ retains moderate affinity for renal PTH receptors, but does not have any agonist activity; weak receptor binding activity is retained in a fragment as small as PTH(25-34) (M. Rosenblatt, et al., 1980, *Endocrinol.*, 107:545-550). In contrast, carboxyl-terminal truncations of PTH(1-34) produce agonists with progressively lower affinities. PTH(1-25) is reported to be essentially inactive (Segre, G.V. et al., 1979, *J. Biol. Chem.*, 254:6980-6996; Rosenblatt, M., 1982, *Endocrinology of Calcium Metabolism*; Parsons, J.A., ed. Ravens Press, NY, 103-142; Tregear, et al., 1973, *Endocrinol.* 93:1349-1353). The principal receptor-binding domain of PTH is reported to include amino acid residues 25-34 and the principal activation domain is reported to include amino acid residues 1-6.

The term "parathyroid hormone" (PTH) encompasses naturally occurring human PTH, as well as synthetic or recombinant PTH (rPTH). Further, the term "parathyroid hormone" encompasses full-length PTH(1-84) as well as PTH fragments. It will thus be understood that fragments of PTH variants, in amounts giving equivalent biological activity to PTH(1-84), can be incorporated in the formulations according to the invention, if desired. In this context, the term "biologically active" should be understood as eliciting a sufficient response in a bioassay for PTH activity according to the methods described herein. Fragments of PTH incorporate at least the amino acid residues of PTH necessary for a biological activity similar to that of intact PTH. Examples of such fragments are PTH(1-31), PTH(1-34), PTH(1-36), PTH(1-37), PTH(1-38), PTH(1-41), PTH(28-48) and PTH(25-39).

The term "parathyroid hormone" also encompasses variants and functional analogues of PTH. The present invention thus includes pharmaceutical formulations comprising such PTH variants and functional analogues, carrying modifications like substitutions, deletions, insertions, inversions or cyclisations, but nevertheless having substantially the biological activities of parathyroid hormone. Stability-enhanced variants of PTH are known in the art from e.g. WO 92/11286 and WO 93/20203. Variants of PTH can e.g. incorporate amino acid substitutions that improve PTH stability and half-life, such as the replacement of methionine residues at positions 8 and/or 18, and replacement of asparagine at position 16. Cyclized

PTH analogues are disclosed in e.g. WO 98/05683.

Under some circumstances, PTH is a bone anabolic agent, and promotes bone formation. However, PTH can stimulate bone resorption as well. It has been reported that high-dose, continuous administration of PTH results in a lowered bone mass but low-dose, intermittent administration of PTH can increase bone mass. PTH administered continuously reportedly causes an increase in the number of bone cells, including osteoclasts, and an increase in bone remodeling. These increases reportedly are apparent within hours after PTH administration and persist for hours after PTH is withdrawn. PTH administration intermittently over days in humans and animals reportedly leads to a net stimulation of bone formation. For example, see Neer et al., 2001, N. Engl. J. Med., 344:1434-1441. In contrast, continuous exposure to elevated levels of PTH leads to osteoclast-mediated bone resorption. Several groups have investigated the use of PTH and PTHrP analogues as agents to treat osteoporosis. These efforts are described in U.S. Patent No. 5,747,456; U.S. Patent No. 5,849,695; U.S. Patent No. 4,656,250; U.S. Patent No. 6,051,686; and U.S. Patent No. 6,316,410.

In one embodiment the subject is a bone marrow donor. By enhancing mobilization of bone marrow cells, the need for bone marrow isolation may be obviated. As a result of this mobilization, bone marrow cells leave the bone marrow and enter the blood circulation of the subject undergoing treatment. The circulating bone marrow cells can then be easily isolated using the techniques of the invention or other methods known in the art. For instance, these methods may reduce the need for large bone marrow donations for therapeutic procedures. The methods enable the isolation of hematopoietic stem cells from peripheral blood by encouraging localization from the bone marrow to the blood and thus, eliminating the need for bone marrow donation.

One of skill in the art would be aware of methods for isolating hematopoietic stem cells from peripheral blood. For example blood in PBS is loaded into a tube of Ficoll (Ficoll-Paque, Amersham) and centrifuged at 1500 rpm for 25-30 minutes. After centrifugation the white center ring is collected as containing hematopoietic stem cells.

Hematopoietic progenitor cell manipulation is also useful as a supplemental treatment to chemotherapy, e.g., hematopoietic progenitor cells may be caused to localize into the peripheral blood and then isolated from a subject that will undergo chemotherapy, and after the therapy the cells can be returned (e.g. ex vivo therapy may also be performed on the

isolated cells). Thus, the subject in some embodiments is a subject undergoing or expecting to undergo an immune cell depleting treatment such as chemotherapy. Most chemotherapy agents used act by killing all cells going through cell division. Bone marrow is one of the most prolific tissues in the body and is therefore often the organ that is initially
5 damaged by chemotherapy drugs. The result is that blood cell production is rapidly destroyed during chemotherapy treatment, and chemotherapy must be terminated to allow the hematopoietic system to replenish the blood cell supplies before a patient is re-treated with chemotherapy. This can be avoided using the methods of the invention.

Once the hematopoietic progenitor cells are mobilized from the bone marrow to the
10 peripheral blood a blood sample can be isolated in order to obtain the hematopoietic progenitor cells. These cells can be transplanted immediately or they can be processed *in vitro* first. For instance, the cells can be expanded *in vitro* and/or they can be subjected to an isolation or enrichment procedure. It will be apparent to those of ordinary skill in the art that the crude or unfractionated blood products can be enriched for cells having "hematopoietic
15 progenitor cell" characteristics. Some of the ways to enrich include, e.g., depleting the blood product from the more differentiated progeny. The more mature, differentiated cells can be selected against, via cell surface molecules they express. Additionally, the blood product can be fractionated selecting for CD34⁺ cells. Such selection can be accomplished using, for example, commercially available magnetic anti-CD34 beads (Dynal, Lake Success, NY). In
20 preferred embodiments, however, the methods of the invention may be used to isolate the hematopoietic progenitor cells.

The invention further provides methods of immunizing against and/or treating an infectious disease in an individual. The methods generally involve administering to a subject the compounds of the invention in an amount effective to stimulate hematopoiesis.

25 As used herein, the terms "treatment", "treating", and the like, refer to obtaining a desired pharmacologic and/or physiologic effect. The effect may be prophylactic in terms of completely or partially preventing a disease or symptom thereof and/or may be therapeutic in terms of a partial or complete cure for a disease and/or adverse affect attributable to the disease. "Treatment", as used herein, covers any treatment of a disease in a mammal,
30 particularly in a human, and includes: (a) preventing the disease from occurring in a subject which may be predisposed to the disease but has not yet been diagnosed as having it; (b) inhibiting the disease, i.e., arresting its development; and (c) relieving the disease, e.g.,

causing regression of the disease, e.g., to completely or partially remove symptoms of the disease.

Also suitable for treatment with the methods of the invention are individuals with healthy, intact immune systems, but who are at risk for becoming immune deficient ("at-risk" individuals). At-risk individuals include, but are not limited to, individuals who have a greater likelihood than the general population of becoming immune deficient. Individuals at risk for becoming immune deficient include, but are not limited to, individuals at risk for HIV infection due to sexual activity with HIV-infected individuals; intravenous drug users; individuals who may have been exposed to HIV-infected blood, blood products, or other HIV-contaminated body fluids; babies who are being nursed by HIV-infected mothers; individuals who were previously treated for cancer, e.g., by chemotherapy or radiotherapy, and who are being monitored for recurrence of the cancer for which they were previously treated; and individuals who have undergone bone marrow transplantation or any other organ transplantation.

A reduced level of immune function compared to a normal subject can result from a variety of disorders, diseases infections or conditions, including immunosuppressed conditions due to leukemia, renal failure; autoimmune disorders, including, but not limited to, systemic lupus erythematosus, rheumatoid arthritis, auto-immune thyroiditis, scleroderma, inflammatory bowel disease; various cancers and tumors; viral infections, including, but not limited to, human immunodeficiency virus (HIV); bacterial infections; and parasitic infections.

A reduced level of immune function compared to a normal subject can also result from an immunodeficiency disease or disorder of genetic origin, or due to aging. Examples of these are immunodeficiency diseases associated with aging and those of genetic origin, including, but not limited to, hyperimmunoglobulin M syndrome, CD40 ligand deficiency, IL-2 receptor deficiency, γ -chain deficiency, common variable immunodeficiency, Chediak-Higashi syndrome, and Wiskott-Aldrich syndrome.

A reduced level of immune function compared to a normal subject can also result from treatment with specific pharmacological agents, including, but not limited to chemotherapeutic agents to treat cancer; certain immunotherapeutic agents; radiation therapy; immunosuppressive agents used in conjunction with bone marrow transplantation; and immunosuppressive agents used in conjunction with organ transplantation.

An "immune system deficiency" shall mean a disease or disorder in which it would be useful to boost a subject's immune response for example to eliminate a tumor or cancer (e.g., tumors of the brain, lung (e.g., small cell and non-small cells), ovary, breast, prostate, colon, as well as other carcinomas and sarcomas) or an infection in a subject.

5 The compounds of the invention may be administered to the subject alone or in combination with an antigen, such as a tumor antigen, a viral, bacterial, or fungal antigen or other therapeutic.

 Examples of infectious virus include: *Retroviridae* (e.g., human immunodeficiency viruses, such as HIV-1, also referred to as HTLV-III, LAV or HTLV-III/LAV, or HIV-III; and other isolates, such as HIV-LP; *Picornaviridae* (e.g., polio viruses, hepatitis A virus; enteroviruses, human coxsackie viruses, rhinoviruses, echoviruses); *Calciviridae* (e.g., strains that cause gastroenteritis); *Togaviridae* (e.g., equine encephalitis viruses, rubella viruses); *Flaviridae* (e.g., dengue viruses, encephalitis viruses, yellow fever viruses); *Coronaviridae* (e.g., coronaviruses); *Rhabdoviridae* (e.g., vesicular stomatitis viruses, rabies viruses);
10 *Filoviridae* (e.g., ebola viruses); *Paramyxoviridae* (e.g., parainfluenza viruses, mumps virus, measles virus, respiratory syncytial virus); *Orthomyxoviridae* (e.g., influenza viruses); *Bungaviridae* (e.g., Hantaan viruses, bunga viruses, phleboviruses and Nairo viruses); *Arenaviridae* (hemorrhagic fever virus); *Reoviridae* (e.g., reoviruses, orbiviruses and rotaviruses); *Birnaviridae*; *Hepadnaviridae* (Hepatitis B virus); *Parvoviridae* (parvoviruses);
15 *Papovaviridae* (papilloma viruses, polyoma viruses); *Adenoviridae* (most adenoviruses); *Herperviridae* (herpes simplex virus (HSV) 1 and 2, varicella zoster virus, cytomegalovirus (CMV), herpes viruses); *Poxviridae* (variola viruses, vaccinia viruses, pox viruses); and *Iridoviridae* (e.g., African swine fever virus); and unclassified viruses (e.g., the etiological agents of Spongiform encephalopathies, the agent of delta hepatitis (thought to be a
20 defective satellite of hepatitis B virus), the agents of non-A, non-B hepatitis (class 1 - internally transmitted; class 2 - parenterally transmitted (i.e., Hepatitis C); Norwalk and related viruses, and astroviruses).

 Examples of infectious bacteria include: *Helicobacter pylori*, *Borrelia burgdorferi*, *Legionella pneumophila*, *Mycobacteria* sps (e.g., *M. tuberculosis*, *M. avium*, *M. Intracellulare*, *M. kansasii*, *M. goodii*), *Staphylococcus aureus*, *Neisseria gonorrhoeae*,
30 *Neisseria meningitidis*, *Listeria monocytogenes*, *Streptococcus pyogenes* (Group A Streptococcus), *Streptococcus agalactiae* (Group B Streptococcus), *Streptococcus* (viridans

group), *Streptococcus faecalis*, *Streptococcus bovis*, *Streptococcus*
(anaerobic sps.), *Streptococcus pneumoniae*, pathogenic *Campylobacter* sp., *Enterococcus*
sp., *Haemophilus influenzae*, *Bacillus anthracis*, *Corynebacterium diphtheriae*,
Corynebacterium sp., *Erysipelothrix rhusiopathiae*, *Clostridium perfringens*, *Clostridium*
5 *tetani*, *Enterobacter aerogenes*, *Klebsiella pneumoniae*, *Pasteurella multocida*, *Bacteroides* sp.,
Fusobacterium nucleatum, *Streptobacillus moniliformis*, *Treponema pallidum*, *Treponema*
pertenue, *Leptospira*, and *Actinomyces israeli*.

Examples of infectious fungi include: *Cryptococcus neoformans*, *Histoplasma*
capsulatum, *Coccidioides immitis*, *Blastomyces dermatitidis*, *Chlamydia trachomatis*,
10 *Candida albicans*. Other infectious organisms (i.e., protists) include: *Plasmodium falciparum*
and *Toxoplasma gondii*.

When the cells or any compounds of the invention (referred to as therapeutic
compositions), such as PTH are administered to a subject, the therapeutic compositions may
be administered in pharmaceutically acceptable preparations. Such preparations may
15 routinely contain pharmaceutically acceptable concentrations of salt, buffering agents,
preservatives, compatible carriers, and optionally other therapeutic agents.

The therapeutic composition may be administered by any conventional route,
including injection or by gradual infusion over time. The administration may, depending on
the composition being administered, for example, be oral, pulmonary, intravenous,
20 intraperitoneal, intramuscular, intracavity, subcutaneous, or transdermal. Techniques for
preparing aerosol delivery systems containing active agents are well known to those of skill
in the art. Generally, such systems should utilize components which will not significantly
impair the biological properties of the active agents (see, for example, Sciarra and Cutie,
"Aerosols," in Remington's Pharmaceutical Sciences, 18th edition, 1990, pp 1694-1712;
25 incorporated by reference). Those of skill in the art can readily determine the various
parameters and conditions for producing aerosols without resort to undue experimentation.
When using antisense preparations, intravenous or oral administration are preferred.
The compositions are administered in effective amounts. An "effective amount" is that
amount of a composition that alone, or together with further doses, produces the desired
30 response; e.g. results in an increase in hematopoietic progenitor cells in the bone marrow.
The term "therapeutic composition" is used synonymously with the terms "active
compound", "active agent" or "active composition" and as used herein refers to any of the

active compounds of the invention which produce a biological effect, e.g., PTH, PTH analogues such as those disclosed in patents US4,086,196, US6,541,450, and WO93/06845, incorporated herein by reference, enriched hematopoietic stem cell preparations, etc. In the case of treating a particular disease or condition characterized by immune deficiency, the
5 desired response is any improvement in immune system function. This may involve only an increase in the actual numbers of hematopoietic stem cells, slowing of onset or progression of an infectious disease arising from the immune system dysfunction, temporarily, although more preferably, it involves an actual improvement in the prevention of disease permanently. This can be monitored by routine methods.

10 Such amounts will depend, of course, on the particular condition being treated, the severity of the condition, the individual patient parameters including age, physical condition, size and weight, the duration of the treatment, the nature of concurrent therapy (if any), the specific route of administration and like factors within the knowledge and expertise of the health practitioner. These factors are well known to those of ordinary skill in the art and can
15 be addressed with no more than routine experimentation. It is generally preferred that a maximum dose of the individual components or combinations thereof be used, that is, the highest safe dose according to sound medical judgment. It will be understood by those of ordinary skill in the art, however, that a patient may insist upon a lower dose or tolerable dose for medical reasons, psychological reasons or for virtually any other reasons.

20 The pharmaceutical compositions used in the foregoing methods preferably are sterile and contain an effective amount of therapeutic composition for producing the desired response in a unit of weight or volume suitable for administration to a patient. The response can, for example, be measured by determining the effect on cell mobilization following administration of the therapeutic composition via a reporter system, or by isolating cells and
25 measuring mobility *in vitro*. Other assays will be known to one of ordinary skill in the art and can be employed for measuring the level of the response.

When administered, pharmaceutical preparations of the invention are applied in pharmaceutically acceptable amounts and in pharmaceutically acceptable compositions. Such preparations may routinely contain salts, buffering agents, preservatives, compatible
30 carriers, and optionally other therapeutic ingredients. When used in medicine the salts should be pharmaceutically acceptable, but non-pharmaceutically acceptable salts may conveniently be used to prepare pharmaceutically acceptable salts thereof and are not excluded from the

scope of the invention. Such pharmacologically and pharmaceutically acceptable salts include, but are not limited to, those prepared from the following acids: hydrochloric, hydrobromic, sulfuric, nitric, phosphoric, maleic, acetic, salicylic, p-toluenesulfonic, tartaric, citric, methanesulfonic, formic, succinic, naphthalene-2-sulfonic, pamoic, 3-hydroxy-2-naphthalenecarboxylic, and benzene sulfonic. Also, pharmaceutically acceptable salts can be prepared as alkaline metal or alkaline earth salts, such as sodium, ammonium, magnesium, potassium or calcium salts of the carboxylic acid group.

Suitable buffering agents include: acetic acid and salts thereof (1-2% W/V); citric acid and salts thereof (1-3% W/V); boric acid and salts thereof (0.5-2.5% W/V); and phosphoric acid and salts thereof (0.8-2% W/V).

Suitable preservatives include benzalkonium chloride (0.003-0.03% W/V); chlorobutanol (0.3-0.9% W/V); parabens (0.01-0.25% W/V) and thimerosal (0.004-0.02% W/V).

A variety of administration routes are available. The particular mode selected will depend, of course, upon the particular combination of therapeutic agents selected, the severity of the condition or disorder being treated, or prevented, the condition of the patient, and the dosage required for therapeutic efficacy. The methods of this invention, generally speaking, may be practiced using any mode of administration that is medically acceptable, meaning any mode that produces effective levels of the active compounds without causing clinically unacceptable adverse effects. Such modes of administration include oral, rectal, topical, transdermal, sublingual or intramuscular, infusion, parenteral, intravenous, intramuscular, intracavity, as a feed additive, as an aerosol, buccal, aural (e.g., via eardrops), intranasal, inhalation, or subcutaneous. Direct injection could also be preferred for local delivery to the site of injury.

Although at present subcutaneous administration is routinely employed in the administration of PTH and/or PTHrP, oral administration may be preferred for treatment because of the convenience of the subject (patient) as well as the dosing schedule. Generally, daily oral doses of active compounds will be from about 0.1 microgram per day to 1000 micrograms per day. It is expected that oral doses in the range of 0.5 to 50 micrograms, in one or several administrations per day, will yield the desired results. Dosage may be adjusted appropriately to achieve desired drug levels, local or systemic, depending upon the mode of administration. For example, it is expected that intravenous administration would be from an

order to several orders of magnitude lower dose per day compared to the oral doses. In the event that the response in a subject is insufficient at such doses, even higher doses (or effective higher doses by a different, more localized delivery route) may be employed to the extent that patient tolerance permits.

5 Preferably the polypeptides of the invention are administered intermittently, which is known in the art to promote anabolic efficacy of PTH, PTHrP and its analogues. Preferred intermittent administration schedules include daily, every second day, every third day, twice per week, every fourth day, every fifth day, every sixth day, and once per week.

10 The compositions may conveniently be presented in unit dosage form and may be prepared by any of the methods well known in the art of pharmacy. All methods include the step of bringing the compounds of the invention into association with a carrier which constitutes one or more accessory ingredients. In general, the compositions are prepared by uniformly and intimately bringing the compounds of the invention into association with a liquid carrier, a finely divided solid carrier, or both, and then, if necessary, shaping the
15 product.

 Compositions suitable for parenteral administration conveniently comprise a sterile aqueous preparation of the compounds of the invention. This preparation is preferably isotonic with the blood of the recipient. This aqueous preparation may be formulated according to known methods using those suitable dispersing or wetting agents and
20 suspending agents. The sterile injectable preparation may also be a sterile injectable solution or suspension in a non-toxic parenterally-acceptable dilutant or solvent, for example as a solution in 1,3-butane diol. Among the acceptable vehicles and solvents that may be employed are water, Ringer's solution, and isotonic sodium chloride solution. In addition, sterile, fixed oils are conventionally employed as a solvent or suspending medium. For this
25 purpose any bland fixed oil may be employed including synthetic mono or di-glycerides. In addition, fatty acids such as oleic acid find use in the preparation of injectables. Carrier formulations suitable for oral, subcutaneous, intravenous, intramuscular, etc. are well known in the art.

 Compositions suitable for oral administration may be presented as discrete units such
30 as capsules, cachets, tablets, syrups, elixirs or lozenges, each containing a predetermined amount of the compounds of the invention. Compositions suitable for any pulmonary delivery typically are formulated and/or are contained in a nebulizer.

Other delivery systems can include time-release, delayed release or sustained release delivery systems. Such systems can avoid repeated administrations of the compounds of the invention, increasing convenience to the subject and the physician, yet are constructed to provide the anabolic benefit of the polypeptides of the invention. Many types of release delivery systems are available and known to those of ordinary skill in the art. They include polymer based systems such as polylactic and polyglycolic acid, polyanhydrides and polycaprolactone, nonpolymer systems that are lipids including sterols such as cholesterol, liposomes; phospholipids; hydrogel release systems; silastic systems; peptide based system; implants and the like. Specific examples include, but are not limited to: (a) erosional systems in which the polypeptide is contained in a form within a matrix, found in U.S. Patent Nos. 4,452,775, 4,675,189, and 5,736,152, and (b) diffusional systems in which an active component permeates at a controlled rate from a polymer such as described in U.S. Patent Nos. 3,854,480, 5,133,974 and 5,407,686. In addition, pump-based delivery systems can be used, some of which are adapted for implantation.

Use of a long-term sustained release implant may be particularly suitable for treatment of chronic conditions.

"Long-term" release, as used herein, means that the implant is constructed and arranged to deliver therapeutic levels of the active ingredient for at least 7 days, preferably for 30-60 days and more preferably for longer periods of time (e.g., 12 months or longer).

The implant may be positioned at a site of injury, but need not be. Long-term sustained release implants are well-known to those of ordinary skill in the art and include some of the release systems described above. One such implant system is described in U.S. Patent No. 6,159,490.

Other protocols for the administration of therapeutic compositions will be known to one of ordinary skill in the art, in which the dose amount, schedule of injections, sites of injections, mode of administration and the like vary from the foregoing. Administration of therapeutic compositions to mammals other than humans, e.g. for testing purposes or veterinary therapeutic purposes, is carried out under substantially the same conditions as described above.

The following description of experiments performed is exemplary and non-limiting to the scope of the claimed invention.

Examples

Hematopoietic stem cell frequency is affected by cell autonomous, intrinsic and cell non-autonomous, extrinsic factors. The intrinsic factors have been mapped to specific regions of the mouse genome (de Haan & van Zant, 1997, *J. Exp. Med.*, 186:529-536) that modulate the frequency of hematopoietic stem or restricted progenitor cells, but not both (Morrison et al, 2002, *J. Immunol.*, 168:635-642). Cell cycle dependent kinase inhibitors (CDKIs) that are differentiation stage specific molecular mediators of the hematopoietic stem cell (p21) or progenitor cell (p27) pool size have been identified (Cheng et al., 2000, *Nature Med.*, 6:1235-1240; Cheng et al., 2000, *Science*, 287:1804-1808). However, the extent to which CDKI expression is affected by cell extrinsic cues provided by microenvironmental stimuli remains ill defined. Overcoming CDKI imposed blockade on cell cycle entry in progenitor cells is readily accomplished ex vivo by a number a cytokines produced by multiple cell types in the bone marrow and with measurable levels in serum. In contrast, adult bone marrow derived hematopoietic stem cells are generally difficult to expand ex vivo and few manipulations have resulted in defined stem cell expansion in vivo. Among these are activation of the cell surface Notch1 and Wnt (Reya et al., 2003, *Nature*, 423:409-414; Murdoch et al., 2003, *Proc. Natl. Acad. Sci. USA*, 100:3422-3427) receptors (Stier et al., 2002, *Blood*, 99:2369-2378) and overexpression of the anti-apoptotic protein, bcl-2 (Weissman I et al., 2000, *J. Exp. Med.*, 191:253-264) or the homeobox protein, HoxB4 (Humphries et al., 1999, *Blood*, 94:2605-2612). Whether these molecules are altered in physiologic contexts however, has not been defined and what cell types within the hematopoietic microenvironment participate in altering stem cell numbers in vivo have not been previously characterized. The data presented here demonstrate that osteoblast specific expression of an activated receptor can meaningfully affect both the bone and the bone marrow microenvironments changing bone mass and hematopoietic stem cell pool size. The data presented here indicate that osteoblastic cells are regulatory components of the hematopoietic stem cell niche in the mouse. Perturbation in the number and possibly function of these cells by PPR activation can lead to increased stem cell numbers, apparently by increased self-renewal. Physical interaction of the primitive hematopoietic cells with the niche is required and the Notch signaling pathway is involved. These results define the osteoblast as a regulator of hematopoiesis and support a critical in vivo interplay between bone and bone marrow.

There are several mechanisms by which PPR activation could influence hematopoiesis. Given the association of hematopoietic stem cells with endosteal surfaces in the paratrabecular space, activated PPR induced changes in the architecture of the bone marrow due to increased bone formation, could affect the surface area for support of stem cells. Through the expansion in physical niches capable of maintaining stem cells, a proportionate increase in the number of stem cells could result. Disaggregated coll-caPPR marrow stroma would not be expected to provide a similar increase in such physical niches, however, and yet is able to increase stem cell support ex vivo. The ability of PTH to increase LTC-IC ex vivo further argues against this explanation as it is similarly unlikely that three dimensional niche construction is induced in the two dimensional monolayer culture of stroma used for that assay. An alternative and more likely explanation is the ability of PPR stimulation to induce osteoblast activation thereby indirectly stimulating hematopoiesis.

To what advantage are bone forming elements coupled to hematopoiesis? In a developmental context, mineralization of the bone and increase in bone mass occur during the second trimester when arguably the developmental imperative is to prepare the host for post-uterine life. Within hematopoietic tissue, this involves a shift from predominantly erythrocyte and platelet production to generation of cellular elements of the innate and adaptive immune system. Hematopoietic cell production transitions from the fetal liver as that organ acquires hepatocyte populations and function. Movement of hematopoiesis to the bone marrow and thymus occur in relative tandem, marking changes in the lineage differentiation profiles of blood elements. With the shifting emphasis on mature cell populations, primitive cell lineage outcomes are modulated and stem cell cycling transitions from robust proliferation in the fetal liver to a less vigorous cycling status in the bone marrow. Stem cells eventually acquire the relative quiescence necessary for long-term maintenance of the mature animal (Cheng et al., 2000, Science, 287:1804-1808). The translocation to bone marrow is accompanied by a transition in stem cell cycling and differentiation. The concurrence of these events with building the skeleton may crudely be viewed as pre-natal necessities for encountering the outside world and as roughly needing proportionate scaling with body mass. Failure to achieve bone marrow hematopoiesis due to either aberrant translocalization or osteopetrosis is accompanied by severe hematopoietic defects including in lineages not thought to be directly affected by the inducing molecular defect (Ma Q et al., 1998, Proc. Natl. Acad. Sci. USA, 95:9448-9453; Dai XM et al., 2002,

Blood, 99:111-120). The link of hematopoiesis to bone marrow appears to be critical for normal blood homeostasis.

As hematopoiesis expands its cell repertoire, it produces populations of cells capable of feeding back on stem cell function, modifying it in response to stress. To the extent that the osteoblast represents a mature descendent of bone marrow tissue, it also falls into a paradigm set by other mature bone marrow derived cellular elements. Monocyte/macrophages and T cells are well known to have among their products of activation, cytokines that positively and negatively affect hematopoiesis. PTHrP is increased in response to endotoxic stress in animal models (Funk JL et al., 1997, Endocrinology, 138:2665) and activation of osteoblasts can be increased by PTHr stimulation under conditions of stress (Ryder KD et al., 2000, Calcif. Tissu. Int., 67:241-246). Therefore, osteoblasts may be among bone marrow derived cells capable of providing a regulating effect on hematopoiesis in the varying post-natal environment and of providing that modulation in the immediate microenvironment of the stem cell. The osteoblast may be a mesenchymal stem cell product that can be considered a cell with pleiotropic action including feedback regulation of the cells from which it emerges.

As well as acting as a chemotactic stimulus, SDF-1 α has been shown to increase hematopoietic stem/progenitor cell number and function through inhibition of apoptotic pathways and promoting the cells to cycle (Lataillade et al., 2000, Blood, 95:756-768; Lataillade et al., 2002, Blood, 99:1117-1129). Hematopoietic cells which have been engineered to overexpress the SDF-1 α protein demonstrate increases in number in the adult mouse (Onai et al., 2000, Blood, 96:2074-2080).

Hematopoietic stem cells undergo a development stage-specific translocation during ontogeny and ultimately reside in the adult bone marrow. Maintenance of this highly regenerative cell pool through adult life is dependent upon the relative quiescence of stem cells. The following examples demonstrate new methods for manipulating hematopoietic stem cells for improved therapeutic purposes. The studies focused on whether PTH actions on osteoblastic cells could alter their ability to support hematopoiesis. Hematopoiesis was characterized in a previously described transgenic mouse model in which a constitutively active PPR is expressed in cells of the osteoblastic lineage (Calvi et al., 2001, J. Clin. Invest., 107:277-286).

Example 1: Materials and Methods

Identification of Transgenic Mice. Mice expressing a constitutively active PPR under the control of the 2.3 kb fragment of the mouse $\alpha 1(I)$ collagen promoter (Rossert et al., 1995, J. Cell. Biol., 129:1421-1432) were previously generated (Calvi et al, 2001, J. Clin. Invest., 107:277-286). The transgene construct (Fig. 1a) contained the 2.3 kb fragment of the mouse $\alpha 1(I)$ collagen promoter, 1,880 bp encoding the human mutant PPR HKrk-H223R (Calvi et al., 2001, J. Clin. Invest., 107:277-286), and 750 bp from the pcDNAI vector (which provides a splice sequence and the consensus polyadenylation signal absent in the cDNA encoding HKrk-H223R). Genotyping and determination of number of insertion sites of the transgene were performed as described (Calvi et al., 2001, J. Clin. Invest., 107:277-286). All studies performed were approved by the institutional animal care committee.

Transgene expression. To confirm transgene expression by *in situ* hybridization, a 596 bp probe (DT7) was generated by PCR amplification of pcDNAI vector sequence in the transgene construct using the reverse primer A1 (5'-TAATACGACTCACTATAGGGCGATAAACAAGTTAACAACAACAAT-3' SEQ ID NO:1) and the forward primer S2 (5'-CTTTGTGAAGGAACCTTACT-3' SEQ ID NO:2) (Calvi et al., 2001, J. Clin. Invest., 107:277-286). The A1 reverse primer sequence includes also the T7 RNA polymerase binding site. The PCR conditions were as follows: 94°C for 1 min, 58 °C for 45 sec, 72 °C for 1 min, and an additional 10 min at 72 °C at the end of the 45 cycles. *In situ* hybridizations were performed as described (Calvi et al., 2001, J. Clin. Invest., 107:277-286) using a complementary ³⁵S-labeled riboprobe transcribed from the DT7 PCR product in order to detect expression of the transgene mRNA in stromal cells.

Sample preparation and histologic analysis. For histologic analysis, transgenic mice and sex-matched wild type littermates were sacrificed by cervical dislocation at 12 weeks of age. Tissues from transgenic and wild type littermates were fixed and stored as described (Calvi et al., 2001, J. Clin. Invest., 107:277-286). Hind limbs were decalcified (Calvi et al., 2001, J. Clin. Invest., 107:277-286), and paraffin blocks were prepared by standard histological procedures.

For immunohistochemistry, decalcified sections from wild-type and transgenic mice were stained with the anti-IL-6 gAb M-19 (1:100 dilution), the anti-SCF gAb G-19 (1:100

dilution), the anti-SDF-1 gAb C-19 (1:50 dilution), the anti-Osteopontin gAb P-18 (1:200 dilution), and the anti-Jagged1 rAb H-114 (1:100 dilution) (Santa Cruz Biotechnology, Inc., Santa Cruz, California). The immunohistochemical staining was performed using a biotinylated rabbit anti goat or goat anti rabbit secondary Ab (Vector Labs, Burlingame, California), Horseradish Peroxidase-Conjugated Streptavidin (Jackson Immuno Research, West Grove, Pennsylvania), and AEC Chromogen (Biocare Medical, Walnut Creek, California), or the Vector ABC Alkaline Phosphatase Kit (Vector Labs, Burlingame, California). Slides were counterstained with Mayer's hematoxylin.

- 10 *Cytologic analysis.* For cytologic analysis, hind limbs were dissected from euthanized wild type and transgenic littermates and cells preparations were obtained by flushing the long bones with α -MEM with 10% fetal calf serum (Gibco) and 1% penicillin/streptomycin. Cells were then cultured in tissue culture flasks at an initial concentration of 5×10^6 cells/ml. Medium was changed every three days for two weeks or until stromal layers became
- 15 confluent. Adherent cells were then trypsinized and plated at a concentration of 10^5 cells/ml in multiwell chambers for 7, 14, 28 days and medium was changed every 3 days. For in situ hybridization, cells were rinsed with PBS three times and then fixed for 1 hr at room temperature with 3.7% PBS buffered formaldehyde. For immunohistochemistry, cells were rinsed with TBS.Ca (1mM CaCl_2 , 50mM Tris/HCl pH 7.4, 150mM NaCl) four times and
- 20 fixed for 1 minute with a 1:1 solution of acetone and methanol at room temperature.

- Immunocytochemistry.* Immunocytochemical staining was performed on Acetone:methanol fixed stromal cells. Cells grown in multiwell plates were incubated with anti-SDF-1 goat polyclonal Ab (Santa Cruz Biotechnology, Santa Cruz, CA), 1:50 dilution, for 60 minutes at
- 25 room temperature, and for 45 minutes with a fluorescein-conjugated secondary antibody. Cells were counterstained with Evan's blue. Coverslips were mounted with Vectashield containing DAPI (Vector Laboratories, Burlingame, CA), and slides were examined using a fluorescent microscope with the appropriate filter.

- 30 *Preparation of bone marrow stromal layers.* Mice were euthanized by CO_2 asphyxiation, following which the femurs and tibias were removed and flushed with long-term culture medium (α -MEM with 12.5% horse serum, 12.5% fetal bovine serum, 0.2 mM i-Inositol, 20

μ M folic acid, 10^{-4} M 2-mercaptoethanol, 2 mM L-glutamine and 10^{-6} M hydrocortisone; M5300 Stem Cell Technologies). Mononuclear cells were then cultured in tissue culture flasks at an initial concentration of 5×10^6 cells/ml. Medium was changed every three days for two weeks or until stromal layers became confluent.

5

Flow cytometric analysis. Bone marrow mononuclear cells were isolated as described above. Single cell suspensions were then stained with biotinylated lineage antibodies (CD3, CD4, CD8, Ter119, Gr-1, Mac-1 and B220) and phycoerythrin conjugated anti-Sca-1 and anti-c-Kit (Pharmingen, San Diego, CA). Cells were then labeled with a secondary fluorescein isothiocyanate conjugated streptavidin and analyzed on a FACScalibur cytometer (Becton Dickinson and Co., Franklin Lakes, New Jersey) using Cell Quest software. To assess cell cycle in the primitive population, bone-marrow mononuclear cells (BM MNCs) were stained with lineage antibodies, anti-Sca-1, PyroninY (RNA dye) and Hoechst 33342 (DNA dye) as described (Cheng et al., 2000, Nature Med., 6:1235-1240). For intracellular NICD staining, lin⁻Sca-1⁺c-Kit⁺ cells were permeabilized using the Fix and Perm Cell Permeabilization Kit (Caltag) according to manufacturer's instructions and incubated with 1 μ g of anti-NICD antibody. A secondary goat-anti mouse antibody was then used to detect the anti-NICD.

15

Colony forming unit assay. Mononuclear cells were isolated from the bone marrow and cultured at 10^4 cells/ml in the following medium: 0.9% methylcellulose, 15% FBS, 1% BSA, 10 μ g/ml rh insulin, 200 μ g/ml human transferrin, 10^{-4} M 2-mercaptoethanol, 2mM L-glutamine, 50 ng/ml rmSCF, 10 ng/ml rmIL-3, 10 ng/ml rhIL-6 and 3 units/ml rhEpo (M3434; Stem Cell Technologies, Vancouver, Canada). At day 10, the total number of colonies were counted and reported as total CFU-Cs.

25

Long-term culture initiating cell assay. Murine bone marrow stromal cells from confluent cultures were irradiated (15Gy) and plated at a concentration of 20,000 cells/well in 96-well plates in long-term culture medium. Cells were then seeded into the plates in two-fold serial limiting dilutions and cultured at 33°C/5% CO₂ in a humidified atmosphere. Cultures were

maintained for 5 weeks, changing half of the medium in the wells weekly. Following this, the medium was replaced with methylcellulose containing medium supplemented with recombinant cytokines as described above, then scored for colony growth ten days following the addition of the medium.

5

In vitro treatment with PTH. LTC-IC assays were performed using wild-type stroma and hematopoietic cells. Rat PTH (1-34) (Bachem, Torrance, California) or vehicle was added to each media change either during stroma establishment and/or during culture maintenance to a final concentration of 10^{-7} M. Medium was changed every three days for two weeks or until stromal layers became confluent. For alkaline phosphatase staining, primary mononuclear cells obtained as described above from wild-type and or transgenic littermates were then cultured in 24-well plates at an initial concentration of 5×10^6 cells/ml. At 10 or 14 days after seeding, medium was suctioned off, and the adherent cells were gently rinsed twice in PBS. After fixation in 10% Neutral Formalin Buffer for 30 minutes at room temperature, alkaline phosphatase activity was determined histochemically by incubation for 45 minutes at RT with a mixture of 0.1 mg/ml naphthol AS-MX phosphate (Sigma), 0.5% N,N-dimethylformamide, 0.6mg/ml red violet LB salt (Sigma) in 0.1 M Tris-HCl (pH 8.5). Alkaline phosphatase positive cells were counted at day 10 of culture, when the cultures were subconfluent and individual cells could be identified. For inhibition of γ -secretase activity, 30 μ M of γ -secretase inhibitor II (Calbiochem) dissolved in DMSO was added to the long-term culture medium and LTC-IC assays were performed as described. For non-contact LTC-ICs, bone marrow stromal cell layers were plated into 96-well plates as described. Tissue culture inserts with a 0.2 μ m pore size membrane (Nunc, Naperville, IL) were placed in the wells and bone marrow cells were seeded into the culture inserts.

25

In vivo PTH administration. For PTH administration, 6-8 week old wild type C57/B male mice were used. Rat PTH (1-34) (80 μ g/Kg of body weight) was injected intraperitoneally 5x/ week for 4 weeks (n=5). Control mice (n=4) were injected with an equivalent volume of

vehicle. At the end of the treatment period, ionized serum calcium was measured by the Ciba/Corning 634 Ca^{++} /pH analyzer, and, after euthanasia, the hind limbs and forelimbs were dissected and utilized for cytologic and histologic analysis.

- 5 ***SDF-1 ELISA.*** The amount of SDF-1 released in the cell culture supernatant was estimated by ELISA. SDF-1 concentration was measured in conditioned media from subconfluent primary stromal cells cultures from transgenic and wild type littermates using the Quantikine SDF-1 Immunoassay (R&D Systems, Inc, Minneapolis, MN).
- 10 ***Bone Marrow Transplantation.*** For the competitive transplant studies, 4×10^5 BM MNCs, obtained from CD45.1^+ B6.SJL (Jackson Laboratories, Bar Harbor, ME) mice were mixed with 2×10^5 cells from mock injected or PTH injected CD45.2^+ C57Bl/6 mice. Recipient B6.SJL mice that had been lethally irradiated 24 hours previously with 10Gy of radiation (^{137}Cs source) were injected with cells. After 6 weeks, the mice were euthanized with CO_2 ,
- 15 the BM was removed and flushed with fully supplemented Iscove's Medium. The relative contribution of engraftment from the different cell sources was assessed by flow cytometry utilizing anti-CD45.1 and anti-CD45.2 antibodies (Pharmingen, San Diego, CA). To assess the effects of PTH administration post transplantation, recipient C57Bl/6 mice were lethally irradiated and then injected with 2×10^5 BM MNCs from a donor B6.SJL mouse. Twenty-four
- 20 hours following the injection of the cells, mice were injected with PTH or mock injected as described above for four weeks.

Statistical analysis. Results are expressed as mean \pm s.e.m. Data were analyzed using the unpaired two-tailed Student's *t* test as appropriate for the data set. $P < 0.05$ was considered

25 significant.

Example 2: Transgenic Mouse Experiments

Transgenic mice expressing a constitutively active PPR in cells of the osteoblastic lineage have bone marrow fibrosis and anemia. At 2 and 12 weeks of age, the long bones of the

30 *coll-mutPPR* mice were characterized by abundant trabeculae and marrow fibrosis. At 12 weeks of age, the long bones of the *coll-caPPR* mice were histologically examined and

demonstrated abundant trabeculae with reduced volume of the marrow space in the metaphyseal area. Given the modest contribution of the metaphyseal area to the total marrow space of the long bones, the magnitude of the reduction in the total bone marrow space in the long bones of the adult transgenic mice was minimal. There was an expansion of the trabecular osteoblastic population as defined by staining with osteocalcin, alkaline phosphatase, collagen type I, osteopontin and MMP-13 (Calvi et al., 2001, J. Clin. Invest., 107:277-286). Hematopoietic cells were found in small regions between trabeculae and few adipocytes were seen. Transgenic mice had mild anemia (hematocrit, wild-type, $n=5$: $41 \pm 0.2\%$; transgenic, $n=4$: $35.9 \pm 0.6\%$, $P < 0.005$), a finding also noted in humans with severe primary hyperparathyroidism (Kotzmann et al., 1997, Horm. Metab. Res., 29:387-392; Sikole, 2000, Med. Hypotheses, 54:236-238). This particular phenotype suggests that constitutive activation of the PPR in cells of the osteoblast lineage may alter normal hematopoiesis by affecting the stromal cell population. Bone marrow stromal cells from transgenic mice express the mRNA of the human mutant PPR in culture.

Transgenic mice have an increased number of hematopoietic stem cells in the bone marrow. To elucidate the impact of enhanced activity and number of osteoblasts on hematopoietic stem cells in the transgenic mice, the frequency of hematopoietic stem cells in the bone marrow was first examined by flow cytometry. Analysis of the frequency of the Sca-1⁺lin⁻ subpopulation of cells from the total bone marrow mononuclear cells demonstrated that the transgenic mice had a significant increase in the number of candidate stem cells ($P < 0.01$, Fig. 2a). This proportionate increase had a correspondent increase in the absolute number (mean absolute number per hind limb, wild-type: $32,500 \pm 8,000$ versus transgenic: $65,700 \pm 7,500$). To determine if this corresponded to a functional phenotype, a quantitative, limiting dilution long-term culture initiating-cell (LTC-IC) assay was used that linearly correlates with *in vivo* hematopoietic stem cell (HSC) function (Ploemacher et al., 1991, Blood, 78:2527-2533). The hematopoietic stem cell frequency was examined using the functional measurement of LTC-IC frequency in the lin⁻ fraction of bone marrow mononuclear cells. This confirmed an increase of approximately equivalent magnitude in the frequency of LTC-ICs in the transgenic animals ($P < 0.0001$, Fig. 2b). The magnitude of increase was comparable to the increase seen in immunophenotypically defined primitive cells. As this increase in stem cell frequency could have arisen from an alteration in the cell

cycle profile in the transgenic animals, the proportions of Sca-1⁺lin⁻ cells which were in the G₀ versus G₁ phase were analyzed next. No differences were observed between the transgenic and wild-type mice ($P=0.768$, Fig. 2c). Similarly, measurement of the frequency of hematopoietic progenitor cells using the CFU-C assay demonstrated no difference between the transgenic and wild-type animals ($P=0.573$; Fig. 2d). These data demonstrate the specificity of the expansion to be at the hematopoietic stem cell level. In particular these data demonstrate that cell expansion was not global across differentiated subsets, but was notably restricted to primitive cells.

PTH action on stromal cells through the PPR is sufficient to increase numbers of hematopoietic stem cells in vitro. As the transgenic mice had an increased frequency of hematopoietic stem cells, the mechanism for this enhancement was investigated. Evaluating the ability of bone marrow stromal cells to support LTC-ICs, it was found that stromal cells derived from the transgenic mice demonstrated enhanced LTC-IC support compared with stromal cells from wild-type animals ($P<0.005$, Fig. 3a). Therefore the increased number of primitive cells in the coll-caPPR mice was stroma-determined and was independent of the hematopoietic cell genotype. Due to the transgenic mice having a constitutively active PTH/PTHrP receptor, it was then determined whether or not the addition of exogenous PTH could mimic the previous observations. In these experiments, the stromal cell population was expanded in the presence of PTH, or the LTC-IC assay was performed with PTH in the long-term medium. It was found that the presence of PTH during the expansion of the stromal population from the bone marrow enhanced the ability of the stroma to support LTC-ICs.

Example 3: Transgenic Cell Experiments

PPR transgenic osteoblastic cells highly express IL-6, SCF, and SDF-1.

Immunohistochemistry was used to assess levels of Interleukin 6 (IL-6), kit ligand or Stem Cell Factor (SCF) and Stroma-derived Factor 1 (SDF-1) in the transgenic cells among the metaphyseal trabeculae. These cells have been previously shown by in situ hybridization to be a heterogeneous population of osteoblastic cells (Calvi et al., 2001), and

immunohistochemistry for Osteopontin, a marker of osteoblastic cells, confirmed these data. In wild-type animals, only a few osteoblastic cells express these factors. In contrast, high levels of IL-6 were detected heterogeneously in the osteoblastic cells of transgenic animals. Expression of SDF-1 was diffuse, while SCF was present at high levels mainly in the more mature cells lining the trabeculae. To address whether diffusible cytokines could account for the effect on primitive cells, LTC-ICs were performed with a semi-permeable membrane separating feeder cells from BM MNCs (non-contact cultures) and noted abolition of benefit from the activated PPR ($P=0.982$, Fig. 4). These data indicate the requirement for cell-cell contact or direct primitive hematopoietic cell interaction with a niche cell or matrix component. SCF may be membrane bound as well as freely secreted. However, other candidate membrane restricted mediators of stem cell expansion were investigated.

Transgenic osteoblastic cells produce high levels of the Notch ligand, Jagged1. The Notch signalling pathway, which regulates cell-fate specification in a wide variety of systems (Artavanis-Tsakonas et al, 1999, Science, 284:770-776), is thought to affect HSC self-renewal (Stier et al., 2002, Blood, 99:2369-2378; Varnum-Finney et al., 2003, Blood, 101:1784-1789; Varnum-Finney et al., 2000, Nat. Med., 6:1278-1281; Karanu et al., 2000, J. Exp. Med., 192:1365-1372; Karanu et al., 2001, Blood, 97:1960-1967). Manipulation of Notch signalling has been shown to increase stem cell numbers without expanding mature cells (Stier et al., 2002, Blood, 99:2369-2378; Karanu et al., 2000, J. Exp. Med., 192:1365-1372). Further, the Notch ligand Jagged1 has been shown to be expressed by marrow stromal cells (Karanu et al., 2000, J. Exp. Med., 192:1365-1372; Li et al., 1998, Immunity, 8:43-55) as well as murine osteoblasts (Pereira et al., 2002, J. Cell Biochem., 85:252-258). Notch and cytokine induced signalling pathways have been shown to have a combinatorial effect in regulating hematopoietic cell fate (Varnum-Finney et al., 2003, Blood, 101:1784-1789). It was therefore investigated whether Jagged1 protein levels were altered in the marrow of transgenic mice and observed by immunohistochemistry that overall levels of Jagged1 were dramatically increased. The cells expressing the Jagged1 were osteoblastic, as shown by their morphologic characteristics and staining with anti-Osteopontin antibody. To examine whether the hematopoietic stem cells responded to the increased expression of Jagged1 in the transgenic animals, the level of the Notch Intracellular Domain (NICD) was assessed in the

lin⁻Sca-1⁺c-Kit⁺ HSCs from wild-type and transgenic mice. The anti-NICD antibody has previously been shown to preferentially detect the activated intracellular form of Notch1 (Huppert et al., 2000, Nature, 405:966-970). Whereas wild-type mice had minimal staining for the NICD compared with isotype controls, lin⁻Sca-1⁺c-Kit⁺ cells from transgenic mice had a notable increase in the level of NICD (Fig. 3b). These data suggest a model in which activation of the PPR in the osteoblastic population increases their number and their overall production of Jagged1. This in turn may activate Notch1 on primitive hematopoietic cells resulting in expansion of the primitive cell compartment.

10 **Example 4: *In vitro* PTH Administration**

PTH treatment in vitro reproduces the coll-caPPR effect. Since the coll-caPPR mice represented a genetic means of activating a receptor that could also be activated by endogenous ligand, it was next tested whether the effects of coll-caPPR stroma could be recapitulated through exposure of wild type stroma to PTH. LTC-IC assays were performed using C57Bl/6 stroma expanded *in vitro* in the presence or absence of PTH, after which hematopoietic cells were introduced to the stroma in the presence or absence of PTH. When stroma was grown in medium containing PTH, it closely resembled the LTC-IC results using the coll-caPPR stroma, increasing LTC-IC ($P=0.004$, Fig. 5a). Of note, the effect was not seen using stromal cells that were expanded in the absence of PTH, or when PTH was added at the same time as the hematopoietic cells, suggesting an effect on the composition or activity of the stroma as it matures *in vitro*. To assess whether there was an increase in the osteoblastic cell number in the stromal cell cultures treated with PTH, alkaline phosphatase staining of primary murine stromal cell cultures treated with vehicle or PTH were performed. After 14 days, the cultures were confluent and heterogeneous, and there was an increase in alkaline positive cells in the PTH-treated cultures (Fig. 5b), verifying that activation of PPR induces an increase in the number of osteoblastic cells. To further assess whether the effects of PPR activation on primitive hematopoietic cells were due to Notch pathway activation, long term co-cultures in the presence or absence of a γ -secretase inhibitor capable of blocking Notch1 cleavage (Wolfe et al., 1999, Biochemistry, 38:4720-4727) were performed. Addition of the inhibitor reduced the supportive capacity of PTH treated stroma to baseline levels (Fig. 5c). Therefore, Notch1 activation is necessary for osteoblastic cell induced

increases in primitive hematopoietic cells. Taken together, these results further support the model that PPR activation can increase osteoblastic cells resulting in Notch1 mediated expansion of primitive hematopoietic cells.

5 **Example 5: *In vivo* PTH Administration**

Intermittent PTH treatment of normal mice. As treatment of stromal cells with PTH led to an increase in the ability of the stromal cell population to support hematopoietic stem cells, it was investigated whether these effects could be recapitulated *in vivo*. Wild-type C57Bl/6 mice were injected daily with PTH using an intermittent dosing schedule known to increase
10 osteoblasts, and the frequencies of LTC-ICs in the bone marrow were measured. Whereas a two week PTH treatment period did not result in any significant increase in the hematopoietic stem cell population, treatment of mice for four weeks with PTH resulted in a significant increase in the hematopoietic stem cells over mock injected mice. By four weeks, a significant difference was noted with PTH treated mice having a higher frequency and
15 absolute number of $\text{lin}^-\text{Sca-1}^+\text{c-Kit}^+$ compared with mock treated controls ($P < 0.01$, Fig. 5d). Further, the limit dilution LTC-IC assay demonstrated an increase in stem-like cells ($P < 0.005$, Fig. 5e). To further define that functional stem cells were increased after PTH treatment, an *in vivo* assay of competitive transplantation into secondary recipients was used and a >2-fold increase in HSCs was documented ($P < 0.05$, Fig. 5f). These data provide
20 evidence for an increase in HSCs induced by PTH and also serve to validate the reasonable comparability of the *in vitro* and *in vivo* assays used in these studies. Consistent with observations in the transgenic animals, PTH treatment did not affect the level of hematopoietic progenitors as assessed by CFU-C assay ($P = 0.780$, Fig. 5g). Therefore, pharmacological activation of PPR increased stem cell number, but appeared to do so without
25 a broad hematopoietic cell expansion. These data are most consistent with HSC expansion by enhanced self-renewal, a phenomenon known to result from Notch activation. Of note, there was no evidence of hypercalcemia by serum calcium measurements of the PTH treated animals.

30 *PTH administration in vivo following bone marrow transplantation.* Assessing whether PPR stimulation could affect models relevant to the clinical use of stem cells in humans, the

impact of PTH administration on animals undergoing myeloablation and bone marrow transplantation was assessed. Limiting numbers of bone marrow derived donor cells were used to mimic a setting of therapeutic need. Survival rate at 30 days in control mice receiving mock injections after bone marrow transplantation was 40%. In sharp contrast, animals receiving pulse dosing of PTH had markedly improved outcomes with 100% survival (Fig. 6).

The foregoing written specification is considered to be sufficient to enable one skilled in the art to practice the invention. The present invention is not to be limited in scope by examples provided, since the examples are intended as a single illustration of one aspect of the invention and other functionally equivalent embodiments are within the scope of the invention. Various modifications of the invention in addition to those shown and described herein will become apparent to those skilled in the art from the foregoing description and fall within the scope of the appended claims. The advantages and objects of the invention are not necessarily encompassed by each embodiment of the invention.

All references, patents and patent publications that are recited in this application are incorporated in their entirety herein by reference. We claim:

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